1881 nm Tm:YAG ceramic laser with a volume bragg grating as a cavity mirror

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We demonstrate a narrow linewidth 1881 nm Tm:YAG ceramic laser that combines the advantages of in-band pumping at 1617 nm and volume Bragg grating as a wavelength selection device. With an output coupler of 5% transmission, a maximum output power of 200 mW is obtained at 1881 nm with a linewidth of 0.2 nm.

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As a laser gain host, transparent ceramics have exhibited numerous significant advantages over conventional single crystals, such as rapid and large volume fabrication and extreme flexibility in doping concentration[1–4]. In recent years, with the development of fabrication technologies, highly transparent Tm-doped YAG laser ceramic materials have been manufactured. Many studies have been conducted on the development of Tm:YAG ceramic lasers in the past years[5–9]. Recently, in-band pump configuration has been successfully exploited in 2 µm Tm:YAG ceramic lasers[10,11]. According to the absorption and emission spectra of the Tm:YAG ceramics at room temperature Fig. 1, the third emission peak occurs at around 1.88 µm. Lasers at 1.88 µm have many potential applications due to the strong absorption of liquid water in this region[12]. For example, it can be exploited in the diagnosis of certain medical conditions, such as gastrointestinal inflammation, neoplasia and precise cutting of biological tissue[13]. Furthermore, it is an excellent pumping source for Ho-doped laser materials, whose absorption spectrum spans over 1.86–1.93 µm[14].

Owing to severely re-absorption loss, free-running Tm:YAG ceramic lasers are operated at wavelength longer than 2 µm. Short wavelength elements of the emission spectrum can also been realized through some special approaches. Stoneman and Esterowitz demonstrated continuous tuning in the range of 1.87–2.16 µm in Tm:YAG crystal[15]. More recently, Gao *et al.* showed that Tm:YAG ceramic laser can also be tuned in a wide range from 1.88 to 2.01 µm with an intracavity prism or quartz plate[7,16]. Volume Bragg gratings (VBGs) have attracted much attention for wavelength selection and spectral narrowing benefited from the high damage threshold, low insertion losses, narrow reflection or transmission spectral width and reliable thermal stability[17,18].

We reported a 1617 nm in-band pumped Tm:YAG ceramic of 1881 nm laser with VBG as the cavity mirror. Lasing characteristics of 4 at.% Tm^{3+}-doped YAG were evaluated using output couplers of 5% transmission. The laser had a threshold power of ~2.5 W and generated 200 mW of continuous wave (CW) output power at 1881 nm for 5.2 W of incident pump power at 1617 nm, corresponding to slope efficiency with respect to incident pump power of ~8%.

In order to analyze the laser performance at different wavelengths, the laser gain spectrum was estimated by the effective absorption cross-sections (σ_a)[16], emission cross-sections (σ_e)[16], and the formula as follows[19]:

$$\sigma_{\text{gain}} = \beta * \sigma_{\text{e}}(\lambda) - (1-\beta) * \sigma_{\text{a}}(\lambda), \tag{1}$$

where the inversion parameter $\beta = N_2/(N_1 + N_2) \approx N_2/N$ represents the ratio of the number of excited Tm^{3+} ions, N denotes the thulium dopant concentration, and N_2 is the number of active ions in the excited state.

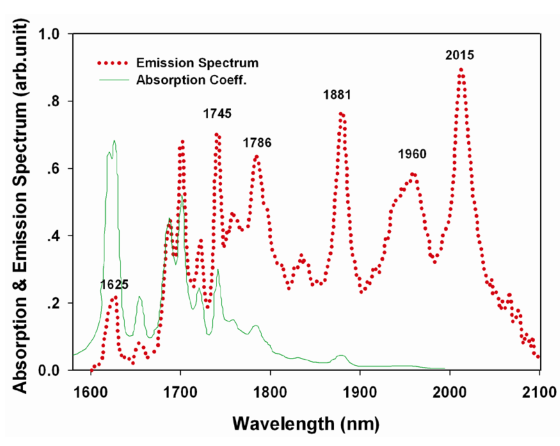

Fig. 1. Absorption (solid curve) and emission (dotted curve) spectra of 4 at.% Tm:YAG ceramic.

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The gain cross-section versus wavelengths was calculated under the same condition with different β values, as depicted in Fig. 2. It can be observed that the laser gain cross-section was always lower at shorter wavelength than that at longer wavelength from 1800 to 2100 nm. It is observed in Fig. 1 that 1881 nm is basically the same emission cross-section as that of 2015 nm, while 2015 nm gain cross-section is twice than that of 1880 nm, which indicates more serious reabsorption loss at 1880 nm. Hence, the gain of 2015 nm easily surpasses that of 1880 nm (i.e., higher absorption cross-section) oscillation under free-running conditions. In order to enhance the resonance effect from cavity mirrors to achieve 1.88 μm lasing, a VBG, which was designed to have a peak reflectivity of 99% at 1880 nm and a spectral width Full Width Half Maximum (FWHM) of 0.5 nm (normal incidence), can be exploited as the cavity mirror. The corresponding reflectivity of such a VBG at 2015 nm is measured to be ~8%, resulting in effective suppression of Tm:YAG oscillating at longer wavelengths.

Figure 3 displays the laser configuration used in our experiment. A simple two-mirror cavity design was employed to evaluate the lasing behavior of the Tm:YAG ceramic. The resonator comprised a VBG (OptiGrate Corp.) acting as the laser input mirror at the normal incidence and a plane output couplers (OC) of 5% transmission at 1850–2250 nm with high reflectivity (>97%) at the pump light. The VBG was measured to have low transmittance losses at the pump wavelength (<6%). It was wrapped with a layer indium foil (0.1 mm in thickness) and mounted in a copper heat sink to allow for good thermal contact. A Tm:YAG ceramic of 4 at.% Tm^{3+} doping was cut and polished to have a cross-section of 2 × 3.5 (mm) and length of 14.5 mm. Both end faces were anti-reflection coated at 1600–2100 nm. To ensure efficient heat removal, the ceramic was wrapped with indium foil (~0.1 mm in thickness) and mounted on a water-cooled copper heat-sink maintained at ~17 °C. The physical length of the resonator was ~20 mm.

A high-power Er:YAG ceramic laser at 1617 nm was constructed in-house as a pump source and the pump laser comprised a plane mirror with high reflectivity at the lasing wavelength of ~1617 nm and high transmission at 1532 nm, and a concave output coupler with transmittance of 30% at the lasing wavelength and the radius of curvature 100 mm. A maximum laser power of 4.56 W at 1617 nm with a bandwidth (FWHM) of <0.5 nm was available, which matches well with the absorption peak of Tm:YAG centered at 1621 nm. The laser output from Er:YAG pump source was collimated and then focused on a beam radius of ~150 μm in the Tm:YAG gain ceramic by pair of 100 mm focal length plano-convex lenses to the Tm:YAG gain ceramic, resulting in a confocal parameter of ~79 mm. Single-pass small signal absorption of the 1617 nm pump light for the Tm:YAG ceramic was measured to be ~85%, and the pump absorption of the ceramic should be close to small-signal absorption under CW lasing condition when the ground-state bleaching is negligible. To enhance the overall absorption efficiency, unabsorbed pump light in the first pass was retro-reflected back into the gain ceramic by the output coupler.

To begin with, an optical spectrum analyzer (AQ6357, Yokogawa) with a resolution of 0.5 nm was used to measure the spectrum of Tm:YAG ceramic laser, with the result shown in Fig. 4. Lasing spectrum was recorded to be 1880.5 nm with a FWHM linewidth of 0.2 nm, corresponding to the third peak of the fluorescence spectrum of the Tm:YAG ceramic at room temperature as shown in Fig. 2. This validates that the suppression effect from the VBG is practical for the realization of 1.88 μm oscillation.

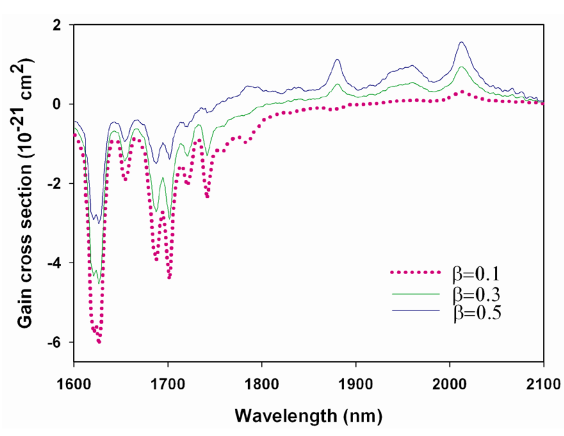

Fig. 2. Gain cross-section spectra of Tm:YAG ceramic versus wavelengths at different inversion factors β.

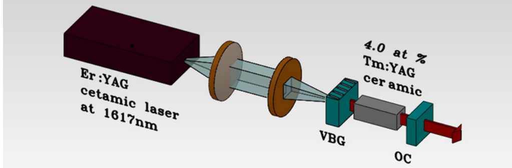

Fig. 3. Experimental schematic diagram of the Tm:YAG ceramic laser.

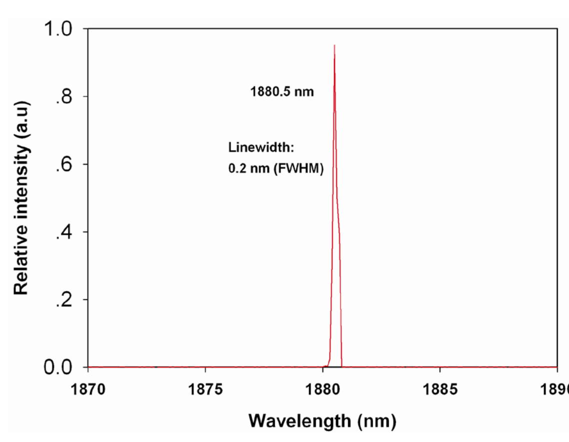

Fig. 4. Laser output spectrum of the Tm:YAG laser at 1880.5 nm.

Figure 5 shows the laser output powers as a function of incident pump power at different wavelengths. It was observed that the laser reached the threshold at an incident pump power of ~2.5 W and produced a maximum CW output of ~200 mW at 1880.5 nm for 5.2 W of incident pump power at 1617 nm, corresponding to a slope efficiency with respect to incident pump power was ~8%. The output power was essentially linear with respect to the incident pump power, suggesting that there is room for further power scaling in output power by simply increasing the incident pump power.

In order to evaluate the lasing performance of the same Tm:YAG ceramic at 2000 and 2015 nm, we employed input mirrors with different center wavelengths and output couplers with the same transmission of 5% under the same cavity length as shown in Fig. 3. It appears that output power decreased as the emission wavelength was shifted to short wavelength inset in Fig. 5. Besides, there was a dramatic reduction in the slope efficiency for 1881 nm laser, which may also be attributed to more pronounced re-absorption loss resulting from increased thermal loading on the ceramic.

The influence of reabsorption loss on laser threshold performance at different wavelengths is further evaluated. The corresponding threshold power of Tm:YAG lasers taking the reabsorption loss into consideration can be expressed as[20]

$$P_{th} = \frac{\pi h\nu_p(\omega_l^2+\omega_p^2)[L+T+2Nlf_1\sigma_{gain}]}{4\tau\eta_a f_2\sigma_{gain}}, \qquad (2)$$

where ν_p is the pump laser frequency, ω_p and ω_l are the pump beam waist and laser beam waist, respectively, L is the cavity loss, T is the transmission of the output coupler, l is the laser crystal length, N denotes the thulium dopant concentration, f_1 and f_2 are the Boltzmann occupation factors of the lower and upper laser level, respectively, σ_{gain} is the gain cross-section, η_a is the fraction of pump light absorbed by the laser medium, τ is the fluorescence lifetime, and h is Planck's constant.

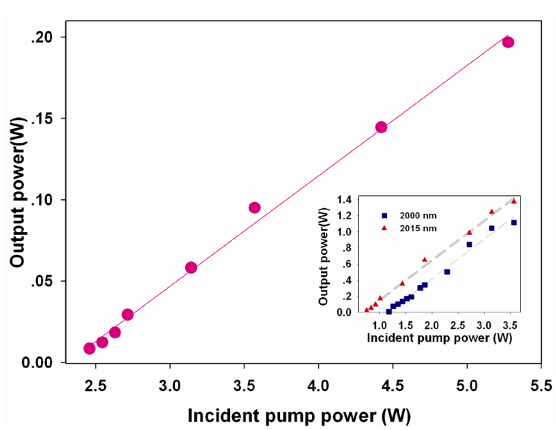

Fig. 5. Laser output power as a function of incident pump power for 4 at.% concentration Tm:YAG. Inset: Output power versus incident pump power of the Tm:YAG ceramic laser at 2000 and 2015 nm.

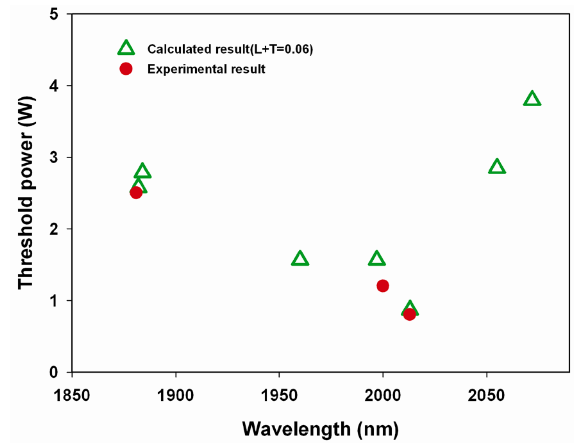

Fig. 6. Laser threshold versus wavelength predicted for the in-pumped Tm:YAG ceramic lasers.

Based on the formula and the energy data of transitions from $^3F_4$ to $^3H_6$ manifold in Tm:YAG[21], we calculated the threshold power of Tm:YAG at different emission wavelengths, as shown in Fig. 6 (green triangle). Experimentally obtained threshold powers at 1881, 2000, and 2015 nm are also shown in Fig. 6 (red circle), which indicates good agreement with the theoretical values. It is evident from Fig. 6 that the laser threshold power greatly decreases when the laser wavelength increases from 1880 to 2015 nm, which can be attributed to the diminution of reabsorption loss and augmentation of the gain cross-section. Beyond 2015 nm, the threshold powers show a sharp increase due to drop in gain cross-section, as shown in Fig. 2.

In conclusion, we demonstrate a narrow linewidth CW laser operating at 1881 nm by using a reflective VBG as resonator mirrors and a highly doped Tm:YAG ceramic as an active media, which is resonantly pumped by an Er:YAG ceramic laser at 1617 nm and by using a reflective VBG as resonator mirrors. A maximum CW laser output power of 200 mW at 1881 nm is achieved for 5.2 W of incident pump power with a slope efficiency of ~8% by using an output coupler of 5% transmission. Furthermore, the influence of reabsorption on threshold pump intensity is also analyzed for different wavelengths. A dramatic increase in threshold pump power and a decrease in slope efficiency at 1881 nm suggest that reabsorption process plays an important role in this laser system. Laser performance is further improved by optimizing Tm^{3+}-doping concentration and hence reduced thermal load and reabsorption.

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